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Process situation assessment: From a fuzzy partition to a finite state machine

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Abstract

Process situation assessment plays a major role in supervision of complex systems. The knowledge of the system behavior is relevant to support operators in their decision tasks. For complex industrial processes such as chemical or petrochemical ones, most of supervision approaches are based on data acquisition techniques and specifically on clustering methods to cope with the difficulty of modeling the process. Consequently, the system behavior can be characterized by a state space partition. This way, situation assessment is performed online through the tracking of the system evolution from one class to another. Furthermore, a finite state machine that is a support tool for process operators is elaborated to model the system behavior. This article presents theoretical aspects according to which the intuition that the trajectory observation of a dynamical system by a sequence of classes, to which the actual state belongs, gives valuable information about the real behavior of the system is substantiated. Thus, practical aspects are developed on the state machine construction and illustrated by two simple applications in the domain of chemical processes.

Keywords: Situation assessment; Fuzzy clustering; Finite state machine

1. Introduction

Complex industrial processes are usually monitored through data acquisition information systems combined with visualization devices. By this way the operators can have a more or less precise vision of the behavior of the process at each observation time. Obviously complex processes are locally controlled by taking advantage of closed loop control systems. The task of the human operator is required when there is either a desired change in the situation or when a conflict or failure occurs. The concept of "situation assessment" has been introduced as a basis for eventual decisions to be applied by the operator, or, in some cases, to close automatically the upper loop by a specially designed supervision system. Fig. 1 shows in a lower level the automatic control loops and in an upper level the supervision loop, where the human operator closes totally or partially it.

The upper supervision loop must handle with the concept of situation or functional state, as "normal", "degraded", "failure", … . The possible situations always belong to a finite discrete set and transitions between the functional states are caused by controllable or uncontrollable actions linked with events in the process. Therefore, discrete event systems modeling tool can naturally be used to model the supervised process.

This paper studies the theoretical and practical steps necessary for the construction of a finite state machine or automaton that, by exhibiting the present situation (functional state) and the possible expected transitions, will help the human operator in the online monitoring task.

The first step is to identify the functional states of the process, this must be done offline. A database collected during past experimental runs of the process or by

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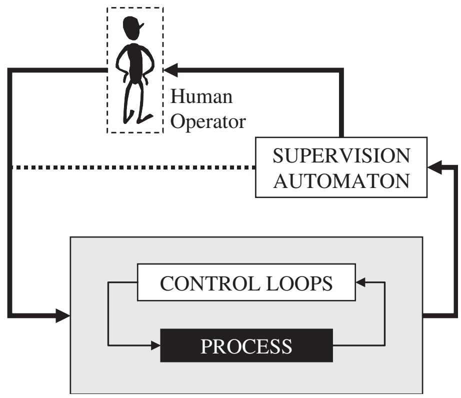

Fig. 1. Supervison and automatic control loops.

simulation is the first requirement. If the collected data correspond uniquely to normal operation, only the situations corresponding to it could be represented as states and any deviation from them will be considered as a failure. Further analysis of the data corresponding to the failure can give rise to the determination of more states. This task theoretically consists on a partition of the real state space of the process, which will be achieved by a learning procedure, generating classes.

The second step is to develop an algorithm for the online recognition of the current state of the process. Generally, this algorithm must process only available online data yielded by the sensors installed on the real plant.

The third step is to determine offline the possible transitions between the states of the automaton and to characterize online the events that cause the transitions; this is performed using estimates of the transition actions.

The basic principle of the proposed supervision approach consists in observing the trajectory of a dynamical system by a sequence of classes to which the actual state belongs. A particular care must be given to the human interface so that the essential information for supervision can be visualized and interpreted, as well as to show the current situation as to predict possible future behaviors of the system.

The next section of this paper describes from a theoretical point of view how the behavior of a dynamical system can be handled through a sequence of classes issued from a state space partition. Section 3 proposes an approach based on fuzzy logic theory to identify the partition. Then, Section 4, focuses on the identification of the transitions between classes. Two case studies are discussed in Sections 5 and 6 in order to illustrate the proposed approach. Concluding remarks are drawn in Section 7.

2. From continuous to discrete state systems

2.1. Dynamical systems

Theoretically a discrete time dynamic system is represented by the recurrent Eq. (1) where x is the state, and u the value at each instant t_k of control vector or input:

$$x(t_{k+1}) = f[x(t_k), u(t_k)]. \tag{1}$$

The system is observed through measurement devices that produce at each measurement instant t_{m} the output:

$$y(t_{\mathrm{m}}) = g[x(t_{\mathrm{m}}), u(t_{\mathrm{m}})]. \tag{2}$$

In Eq. (2), the presence of the input u stands because the observations upon the process include knowledge of the control actions.

Generally, $x \in X^N$; $y \in Y^M$; with $M \leqslant N$ where X^N is a N dimension space obtained by the Cartesian product of N "marginal" subspaces X_i; $i = 1, \ldots, N$. Each marginal subspace has its own description whether it is quantitative (continuous or discrete, and either finite, bounded, infinite, compact, etc.) or qualitative (symbolic, ordered, finite, etc.).

It shall be reminded that the state x of a system is the sufficient information that enables to know its future trajectory produced by future inputs u. In the case of uncertain (stochastic) systems this is called the *Markovian* property.

Consider a continuous system whose state can only be accessed through a partition of the state space. The system generates an event whenever the system trajectory crosses one of the partition borders (Lunze, 1999). Therefore, the problem of supervision concerns to determine the current class in the partition of the state space and to predict the event sequences that can be generated by the future inputs from the present class of states. The initial class of the partition does not define the initial system state unambiguously but only restricts the initial state to a partition. Then, when predicting the system behavior, the set of all state trajectories that start on this initial class have to be considered.

The question is to know under what conditions, on the vector field of the system and on the state partition, the future event sequence is unique i.e. the class sequence is unique. Let us assume that the vector field generated by Eq. (1) satisfies a Lipschitz condition so that it has, for all initial conditions $x_0 \in X^N$, a unique solution.

2.2. Trajectories and state space partition

Let us impose to the state space X^N to be fully partitioned into K disjoint sets C_i with $i = 1, \ldots, K$ that satisfy the conditions $C_i \cap C_j = \varnothing$, $i \neq j$ and $\bigcup_i C_i = X^N$.

Let $x_{[t_0,t_k]} = \{x_0, x_1, \ldots, x_k\} \in X^N \times X^N \times \underset{k+1}{\cdot \leftrightarrow \cdot} \times .X^N$ be a trajectory starting at time t_0 and lasting until time t_k in the state space X^N of the system given by Eq. (1). The set of all such trajectories is called T_0^k, it is the submanifold induced by x_0 included in the manifold defined by all the solutions of (1).

Definition 1. The *length* of a trajectory starting at $y \in C$, $C \subset X^N$ is $d[t_0, t_k|y] = \int_{t_0}^{t_k} x(t|y)\,dt$ and a measure called *volume* of the submanifold induced by $C \subset X^N$ is